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APPENDIX G
CAP DESIGN AND IN SITU TREATMENT OPTIONS EVALUATION

Lower Passaic River Study Area
Draft Feasibility Study

Prepared for
Lower Passaic River Cooperating Parties Group
New Jersey

Prepared by

AECOM

125 Broad Street, New York, NY 10004

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ACRONYMS AND ABBREVIATIONS

cfs	cubic feet per second
COCs	Contaminants of Concern
CPG	Lower Passaic River Cooperating Parties Group
CSM	Conceptual Site Model
ENR	Enhanced Natural Recovery
EPA	U.S. Environmental Protection Agency
EPRI	Electric Power Research Institute
FS	Feasibility Study
foc	fraction organic carbon
LPR	Lower Passaic River
NAPL	Non-aqueous phase liquids
PCBs	Polychlorinated Biphenyls
RI	Remedial Investigation
RM	River Mile
SWAC	Spatially-weighted Average Concentration
TCDD	Tetrachlorodibenzo-p-dioxin
USACE	U.S. Army Corps of Engineers
USGS	U.S. Geological Survey

1 INTRODUCTION

This appendix presents a summary of the evaluations of capping as a remedial technology for the alternatives for the feasibility study (FS). Placement of engineered caps within the Lower Passaic River (LPR) would isolate contaminated sediments that would be exposed once dredging has taken place. Additional functions of the cap would be to prevent resuspension and transport of exposed sediments under stresses created by river flows, currents, waves, ice, and vessel "prop wash." The cap would be designed to limit the migration of contaminants from the underlying sediments into the bioactive zone and into the water column in all remedial areas and would provide a surface that would not preclude re-colonization by benthic communities in ecological exposure areas (e.g., mudflats).

1.1 DEFINITIONS

Capping is a demonstrated remedial technology for containing chemicals in sediment and preventing or reducing the exposure and mobility of those sediment chemicals from their existing location (U.S. Environmental Protection Agency [USEPA], 2005). Capping can also be done to re-establish sediment elevations after dredging and to facilitate re-establishment of subaqueous vegetation or other ecological features. It is one of the most commonly evaluated and implemented remedial technologies for contaminated sediments. Sediment containment is usually achieved via the placement of a subaqueous covering or a cap of clean material over contaminated material that remains in place.

A large number of sediment caps have been successfully implemented (NRC, 2007). The ability to implement capping is influenced by physical constraints (e.g., slopes, obstructions, stable placement environments). Capping is generally suitable in environments (or at depths) where navigation or other public uses would not be physically impeded. The bathymetric, hydrodynamic, slope stability, and biological conditions, as well as commercial/public land use would need to be considered in the engineering design. An engineered cap design specifies material types, gradation, thickness, armoring requirements, design elevation ranges, placement requirements, and other design parameters. For example, the cap design for deep waters would be different from designs for intertidal and shallow subtidal areas of high habitat importance and areas that have the potential for appreciable episodic erosion.

1.2 CAPPING GUIDANCE DOCUMENTS

The U.S. Army Corps of Engineers (USACE) and USEPA have developed detailed guidance for subaqueous dredged material capping and in situ capping for sediment remediation. Guidance documents that provide procedures for site and sediment characterization, cap design, cap placement operations, and monitoring for capping include, among others: Contaminated

Sediment Remediation Guidance for Hazardous Waste Sites (USEPA, 2005), Guidance for Subaqueous Dredged Material Capping (Palermo, et al., 1998a), and Guidance for In Situ Subaqueous Capping of Contaminated Sediments (Palermo, et al., 1998b).

1.3 SUMMARY OF CAPPING PROJECTS IN USEPA REGION 2

Engineered caps have been or are proposed components of the remedies at other contaminated sediment sites in USEPA Region 2. These sites include Onondaga Lake, Grasse River, Upper Hudson River, and Gowanus Canal in New York State, and Berry's Creek in New Jersey. Information on each of these sites can be found in various USEPA references (e.g., 2013a, 2013b).

2 CAPPING FUNCTIONS AND OBJECTIVES

A summary of the functions and objectives of capping as a component of the remedial alternatives evaluated in this FS, and which would be carried into remedial design, is presented below.

2.1 CAPPING FUNCTIONS

In situ capping refers to the placement of a subaqueous covering or cap of clean material over contaminated sediment that remains in place. Caps are generally constructed of granular material, such as clean sediment, sand, or gravel. A more complex cap design can include geotextiles, liners, and other permeable or impermeable elements in multiple layers that may include additions of material to attenuate the flux of contaminants (e.g., activated carbon). Depending on the contaminants and sediment environment, a cap is designed to reduce risk through the following primary functions (USEPA, 2005):

- Physical isolation of the contaminated sediment sufficient to reduce exposure due to direct contact and to reduce the ability of burrowing organisms to move contaminants to the surface.
- Stabilization of contaminated sediment and erosion protection of sediment and cap, sufficient to reduce resuspension and transport to other sites.
- Chemical isolation of contaminated sediment sufficient to reduce exposure from dissolved and colloidally bound contaminants transported into the water column.

2.2 PERFORMANCE CRITERIA FOR CAPPING

This section summarizes performance standards to be used during remedial design as well as potential cap performance threshold values.

As noted in Section 2.1 above, the primary functions of the cap would be to provide both long-term physical and chemical isolation of contaminated sediments. The cap should be stable from physical forces such as river flows, wind, ice, and vessels and a return period of 100 years is typically used in modeling and design to ensure that more frequent events don't result in cap failure. The cap should also be designed to result in long-term (e.g., 100 years or more) control of flux and resuspension of contaminants from underlying sediments into the upper portions of the cap and overlying water. The performance threshold values (or cap effectiveness criteria) for chemical isolation should be established as sediment concentrations that should not be exceeded within the bioactive zone or habitat layer of the cap. These threshold values should generally be based on the site-specific sediment criteria used to establish the remedial areas or the predicted post-remedy average sediment concentrations resulting in acceptable risk reduction such that following placement of clean material during construction, predicted long-term concentrations in the bioactive zone don't exceed these values.

For the purposes of this FS, the following contaminants of concern were evaluated for an assessment of cap effectiveness: dioxins/furans (2,3,7,8-TCDD) and PCBs. For 2,3,7,8-TCDD, a cap threshold value of 50 ng/kg is used in this FS to provide a degree of conservatism in that this value is one order-of-magnitude lower than the remedial action level used to develop remedial areas under Alternative 2 (500 ng/kg). Based on model projections presented in the FS, use of an action level of 500 ng/kg to define remedial (dredge/cap) areas is expected to result in a spatially-weighted average concentration (SWAC) of approximately 50 ng/kg in the top 2 centimeters (cm), which in turn is expected to result in significantly reduced risks from fish consumption to levels below the upper end of USEPA's acceptable risk range. Thus, a proposed cap threshold value of 50 ng/kg is considered appropriate (and conservative) for meeting long-term risk reduction goals.

For PCBs, contributions from other sources both upstream of the LPR Study Area and from Newark Bay (NY/NJ Harbor) would be expected to continue to impact surficial sediments within the LPR Study Area. Thus, the background or upstream concentration of 800 ug/kg (maximum surface sediment concentration upstream of Dundee Dam after removing outlier of 5,110 ug/kg) as presented in the LPR Study Area Baseline Human Health Risk Assessment (AECOM [in prep]) and LPR Study Area Baseline Ecological Risk Assessment (Windward [in prep]) is used in this FS for comparison to cap model predictions.

3 CAP LAYER COMPOSITION

Caps may be designed with different layers to serve the primary isolation and stabilization functions discussed in Section 2.1. In some cases, a single layer may serve multiple functions. A summary of each of the typical cap layers is provided below.

3.1 MIXING LAYER

During cap placement, sediment resuspension and mixing of cap material and softer underlying sediments being capped may occur. The degree of mixing depends on site conditions as well as the physical nature of the materials and the methods of placement. At the Soda Lake site in Wyoming, for example, it was found that applied sand penetrated into underlying soft and unconsolidated sediment up to 2 to 4 inches (EPRI, 2007). For the purpose of this FS, a 3-inch mixing layer is assumed for caps in deeper water areas. A mixing layer is not included in the conceptual cap design in mudflat areas as shallow water and operational controls (e.g., placement in thin lifts) would be expected to result in negligible mixing of underlying sediments into the cap material.

3.2 CHEMICAL ISOLATION LAYER

The chemical isolation component of the cap controls the movement of contaminants by advection, diffusion, and dispersion. Advection is a transport mechanism of a substance by a fluid due to the fluid's bulk motion. In the sediments, advection of underlying groundwater or porewater can result from upward flow of groundwater or from consolidation of the contaminated sediment layer due to cap placement. Diffusion is a movement of particles of a fluid from a place of higher concentration to a place with lower concentration by random molecular motion. Dispersion refers to the spreading and mixing caused by molecular diffusion and by the variations in velocity with which water moves at different scales.

In the cap's chemical isolation layer, porewater contaminant concentrations decrease as porewater moves up through the isolation layer due to advection, dispersion, and diffusion. In the bioactive zone, the fraction organic carbon (foc) is generally higher than in the chemical isolation layer below (bioturbation will tend to increase organic carbon levels). Therefore, at the bottom of the bioactive zone, although porewater concentrations continue decreasing, sediment concentrations of organic contaminants increase due to the sediment's higher organic carbon fraction and greater affinity to organic contaminants; as porewater then continues to migrate upward through the bioactive zone, its contaminant levels continue to decrease. For inorganics, sediment concentrations are calculated based on the predicted porewater concentrations and partitioning without reference to the sediment's organic carbon fraction. Therefore, sediment concentrations decrease throughout the entire cap proportionally to decreases in porewater concentrations.

A 12-inch thickness is typical for the chemical isolation layer at many contaminated sediment sites and is the assumed thickness of the isolation layer for this FS. A preliminary analysis of the chemical isolation layer is presented in Section 4 of this appendix.

3.3 ARMOR (EROSION PROTECTION) LAYER

An armor layer (or erosion protection layer) is required to prevent erosion of the cap material when exposed to high shear stresses, such as those caused by high river flows, propeller wash, or other environmental forces. The armor layer must be designed to resist the shear forces that will occur at the riverbed. The shear force is driven by several factors; these include the velocity and depth of the water, the slope of the river bottom, and the properties of the armoring material.

For the purposes of this FS, an armor layer ranging in thickness from 6 to 12 inches is assumed. As discussed further in Section 5 of this appendix, the armor layer would be designed to resist shear forces caused by flood conditions; environmental factors from sources other than flooding (including ice scour, wind effects and propeller wash) are not expected to be of sufficient magnitude to control the design of the armor layer. The need for geotextile between the isolation layer and armor layer and/or modification of material gradation and thickness (i.e., filter criteria analysis) will be assessed during design. A preliminary analysis of the armor layer is presented in Section 5 of this appendix.

3.4 BIOTURBATION/HABITAT LAYER

The migration of sediment contaminants to overlying water can increase due to bioturbation processes. The depth to which aquatic organisms that live in or on bottom sediment will burrow depends on the species' behavior and the characteristics of the substrate (e.g., grain size, compaction, and organic content). Although marine organisms generally burrow to greater depth than freshwater organisms, bioturbation depths in suitable substrates are typically less than 2 to 6 inches. As discussed in the draft Baseline Ecological Risk Assessment for the LPR Study Area (Windward [in prep]), the current benthic invertebrate community is concentrated in the upper 2 cm of bedded sediment based on sediment profile imaging and other lines of evidence. For evaluating future conditions in areas capped with clean material, a bioactive zone of up to 4 inches (10 cm) is conservatively assumed in the cap model in this FS (and was also the depth utilized by USEPA in its preliminary cap modeling in the Focused FS [The Louis Berger Group, 2014]). Although 4 inches is assumed for the bioactive zone in the model, the conceptual cap configuration in this FS assumes placement of up to 6 inches of habitat layer substrate in mudflat areas. The details of the habitat layer would be determined during remedial design.

3.5 OTHER CONSIDERATIONS

Consolidation occurs whenever vertical effective pressure within a layer of soil is increased for any reason. The increase in effective pressure causes subsidence in two ways: the expulsion of water from voids within the soil layer (known as primary consolidation), followed by continued long-term creep (known as secondary consolidation). Primary consolidation usually accounts for the bulk of total consolidation, with secondary consolidation often being an order-of-magnitude less than the primary. However, in highly organic soils (e.g., peat), the magnitude of the secondary consolidation can equal or exceed that of the primary consolidation. Sites with soft sediments will typically undergo some consolidation of the underlying sediment during and after cap placement. Even where excavation has taken place prior to placement of the cap and there is no net fill, consolidation will occur if (as is typical) the density of the cap material is greater than that of the excavated material.

Cap-related settlement may occur because the cap itself, the underlying sediments, or both may consolidate over time. Design issues resulting from consolidation include consideration of whether consolidation of the capping material itself reduces the effectiveness of the chemical isolation layer, whether consolidation of the underlying sediment causes an increased contaminant load as porewater is expelled, and whether the integrity of the chemical isolation layer is affected if the magnitude of consolidation varies across the cap.

If consolidation of the cap itself is expected to occur, and the magnitude of the consolidation is sufficient to reduce the effectiveness of the chemical isolation layer, a consolidation layer may be included to offset this impact. However, for caps constructed entirely of sands and gravels, consolidation within the cap is typically negligible as displacement of water within the cap occurs during placement. A consolidation layer is not included in the conceptual cap design because the proposed cap is to be constructed of sand and gravel materials, which are not susceptible to long-term consolidation. Should the cap design be altered to include fine-grained materials (potentially including some cap amendment materials), the need for a consolidation layer will be re-evaluated during design.

Consolidation of the underlying sediment beneath the cap will result in the expression of porewater into the cap. Depending on the mass of contaminants in the expressed porewater and geophysical considerations driving the design of the chemical isolation layer (e.g., the upwelling velocity), the expression of porewater during consolidation of the underlying sediment may reduce the overall effectiveness of the cap. The steady-state isolation cap model discussed in Section 4 is not sensitive to consolidation *per se*. Therefore, for the purpose of this FS, a separate consolidation layer is not included in the conceptual cap configuration. However, the impacts of consolidation-induced porewater expression on cap effectiveness will be evaluated during detailed design, as needed, with the transient cap model.

Consolidation of the underlying sediment will not be uniform for several reasons (varying thickness of compressible layers, changes in cap thickness and material, etc.), which may cause differential settlement across the cap. Depending on the magnitude of the differential settlement and the horizontal distance over which it occurs, the integrity of the cap could be impacted. The impact of differential settlements can be mitigated or eliminated through various design measures, such as modifications to dredging or capping slopes, dredge cut depths, and cap placement lift thicknesses. Furthermore, granular caps are "self-healing," in that the cap material is free to reshape itself as small, slow movements occur. Geotechnical investigations and analyses would be conducted during remedial design to evaluate the magnitude of differential settlements, assess potential impacts to cap viability, and consider potential means of eliminating or remediating differential settlements.

3.6 OVERALL CAP CONFIGURATION

Consideration of all cap components independently is the most conservative design approach for an engineered cap. In general, the total cap thickness is the sum of the thicknesses for each of the layers discussed above.

For the alternatives in this LPR FS, two different conceptual cap configurations are proposed for mudflat areas and for deeper water areas. The cap proposed for mudflat areas (see Figure 3-1a below) would consist of a chemical isolation layer (12 inches), armor layer (6 inches), and bioturbation/habitat layer (up to 6 inches) resulting in a preliminary total cap thickness of 2 feet. For deeper water, high velocity areas (see Figure 3-1b below), it is assumed that the armor layer would be 12 inches and that bioturbation would be negligible. Therefore, the cap proposed for deeper water areas would consist of a combined mixing layer (3 inches) and chemical isolation layer (12 inches), armor layer (12 inches), and a contingency for up to 3 inches of material to serve as the filter layer, resulting in a total cap thickness of 2.5 feet. For costing purposes in this FS (for Alternative 2), cap volumes assume 3 ft of material for all areas, including mudflat areas where re-establishment of grade (elevation) would likely be needed following potential over-dredging and allowing for potential consolidation. The final thickness and composition of each layer for each remedial area will be determined during remedial design.

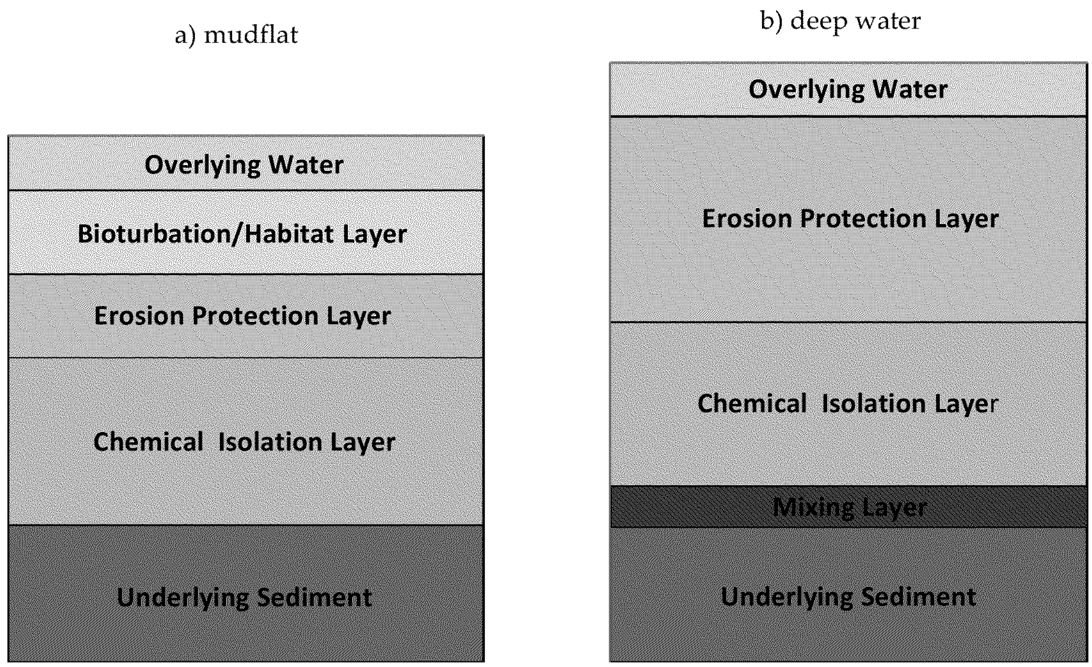

Figure 3-1. Conceptual Cap Configuration a) for mudflat, b) for deeper water

4 PRELIMINARY CHEMICAL ISOLATION CAP MODELING

The following sections describe the input and results of mathematical models used in the preliminary evaluations of the effectiveness of a typical isolation cap for the LPR Study Area. The goal of capping, as noted above, is to limit exposure of waters and benthic substrate to contaminated sediments that remain after dredging has been completed. For this assessment, inputs to the mathematical models are primarily based on information provided in the Interim Conceptual Site Model (CSM) (AECOM et al., 2013) and River Mile (RM) 10.9 Design (CH2MHill, 2013), as well as literature sources. A sensitivity analysis related to key input parameters is also presented below.

4.1 MODEL APPROACH

Preliminary evaluations of the chemical isolation layer for the LPR Study Area have been accomplished through a series of mathematical simulations (Lampert and Reible, 2009b). An analytical steady-state model (Lampert and Reible, 2009a) and the CapSim transient model (Lampert et al., 2012), which allows for time-varying evaluations of contaminant transport in porewater through the cap, were used and the key input parameters are described below in Section 4.2. Results are presented in Section 4.3. In both models, it was conservatively assumed that the concentration in the underlying sediment was constant, without degradation or reduction due to chemical migration out of the sediments. Consolidation and deposition were not modeled and no decay rate was assumed.

For purposes of this analysis, the steady-state model was used for initial screening of contaminants. Two contaminants of concern (COCs) were included in this preliminary modeling: dioxins/furans (2,3,7,8-TCDD) and PCBs. The steady-state model was run for various underlying sediment concentrations, upwelling velocities, and fraction organic carbon levels in the bioactive layer. The steady-state model predictions in the bioactive layer were compared to the proposed cap threshold value for 2,3,7,8-TCDD (50 ng/kg) and background value for PCBs (800 ug/kg). The model runs that exceeded these values at steady state were further evaluated using the transient CapSim model.

The transient model was used to predict the time when exceedances of the cap threshold value for 2,3,7,8-TCDD and background value for PCBs would occur. In the CapSim model, two sand layers were modeled, including a chemical isolation layer with a fraction organic carbon of 0.1 percent and a bioactive layer with a fraction organic carbon ranging from 2 to 5 percent. The CapSim model was run for scenarios (input values) that exceeded the proposed cap threshold value at steady-state. Consistent with cap modeling performed for the design of the RM 10.9 engineered sediment cap (CH2MHill, 2013), all models were run for a period of 250 years, which exceeds the typical cap design performance duration of 100 years. The output from the CapSim model was used to predict whether the sediment concentrations in the bioactive layer exceed the proposed cap threshold value for 2,3,7,8-TCDD and background value for PCB during the model period.

4.2 INPUT PARAMETERS

Key model input parameters are described below and a complete listing of input parameters is presented in Table 4-1.

4.2.1 Cap Thickness

A cap of 16 inches, including a 12-inch isolation layer and a 4-inch bioactive layer, was assumed for this preliminary modeling. Any additional thickness of material that would be placed to accommodate overdredging and/or armoring was not modeled, which adds conservatism to the assumptions. Additional modeling will be performed during the design phase based on additional data gathering and refinements of the cap layers.

4.2.2 Porewater Concentrations

Porewater concentrations of the two COCs in the sediments below the dredge depth were estimated based on an approximate range of underlying sediment concentrations from site data (AECOM et al., 2013), an average foc of 5 percent in the underlying sediments, and literature partition coefficients. For 2,3,7,8-TCDD, a range of underlying sediment concentrations from 100 to 10,000 ng/kg was used in the porewater calculation. This range of concentrations was determined based on a review of sediment concentrations in the 2.5 to 3.5 feet and 3.5 to 5.5 feet depth intervals. Data from near the RM 3.0 source area adjacent to the Lister Avenue site and RM 10.9 area were excluded as these areas have been remediated or are planned for remediation. Although there may be limited data points above the selected range, nearly all of the data are below 10,000 ng/kg, and thus this value is a reasonable upper-bound estimate for this FS evaluation. For PCBs, a range of underlying sediment concentrations from 1,000 to 10,000 ug/kg was used in the porewater calculation.

4.2.3 Upwelling Velocities

As noted in Section 2.1.2 of this FS report, groundwater contribution to the LPR is considered small relative to the freshwater flow that enters the LPR from upstream during average flow conditions. Thus, groundwater upwelling through the sediments is considered to be insignificant for the majority of the LPR study area and upwelling velocities of 1 and 10 cm/year were assumed for the preliminary cap modeling conducted for this FS. In addition, based on data obtained for the RM 10.9 design using near-shore seepage meters, there is a potential for higher upwelling to occur in mudflat areas near shore. To address these areas, upwelling velocities of 100 and 250 cm/year were also evaluated in this preliminary cap modeling.

4.2.4 Fraction Organic Carbon

Estimates of fraction organic carbon (foc) in the bioactive layer (upper portion of the cap) of 2 and 5 percent were used in the model runs to represent a range of potential future conditions. In the chemical isolation layer, an foc of 0.1 percent was conservatively selected based on typical sand cap properties.

4.2.5 Degradation and Depletion

As a conservative approach, no organic contaminant degradation was assumed in the chemical isolation and bioactive layers. Also, an infinite source of contaminant concentrations in the underlying sediment was assumed (i.e., the source of contaminants beneath the cap is not depleted with time).

4.3 MODEL RESULTS

Results of the steady-state modeling are presented in Table 4-2 for 2,3,7,8-TCDD and Table 4-3 for PCBs. The results show that a sand cap of 16 inches, including a 12-inch isolation layer and 4-inch bioactive layer, would be adequate to reduce concentrations in the bioactive layer below the cap threshold value for 2,3,7,8-TCDD and background value for PCBs for most of the modeled underlying sediment concentrations and upwelling velocities. However, the predicted steady-state (maximum) concentrations of 2,3,7,8-TCDD exceed the cap threshold value for the model runs based on the combined scenarios of maximum underlying sediment concentration and upwelling velocities of 100 and 250 cm/yr (Table 4-2). For PCBs, the predicted steady-state (maximum) concentrations do not exceed the background value (Table 4-3).

For the scenarios for which the steady-state (maximum) concentrations exceeded the cap threshold value for 2,3,7,8-TCDD, the CapSim model was run to determine the estimated time when the exceedances would occur. Figures 4-1 and 4-2 present predicted porewater and sediment concentration profiles for different years for 2,3,7,8-TCDD and PCBs, respectively. As shown in Figure 4-1, predicted concentrations of 2,3,7,8-TCDD do not "breakthrough" into the bioactive layer during the 250-year model period. As noted earlier, contaminant concentrations in porewater decrease through the chemical isolation layer and bioturbation layer and contaminant concentrations in sediment decrease through the chemical isolation layer. However, at the bottom of the bioturbation layer, sediment concentrations of organic contaminants would increase due to the assumed higher organic carbon fraction in the bioturbation layer and then decrease as porewater migrates upward through the bioturbation layer (see Figure 4-2).

For all modeled scenarios, the results from the CapSim model indicate that the cap threshold value for 2,3,7,8-TCDD and the background value for PCBs would not be exceeded in the bioactive zone in the first 250 years.

The input parameters for which the model is most sensitive are sediment/porewater concentration, groundwater upwelling velocity, and fraction organic carbon in the bioactive layer. For underlying concentration and upwelling velocity, the scenarios modeled for this FS incorporate the high-end estimates. As stated above, upwelling through the sediments is considered to be insignificant for the majority of the LPR study area (1 to 10 cm/yr). For this range of lower upwelling velocities, no exceedances were predicted at steady-state for 2,3,7,8-TCDD and PCBs .

4.4 CONSIDERATIONS FOR DESIGN

For the purpose of this FS, sediment and predicted porewater concentrations, upwelling velocities, and other input parameters were estimated based on limited data. Following determination of specific remedial areas, additional data would be obtained during design and model input would be refined for each of the remedial areas (or groupings of areas).

In situ treatment (amendments), as discussed below in Section 6.1, has been retained in this FS for areas where a 1 foot sand isolation layer may not achieve cap performance objectives. The extent and types of in situ amendments, if any, would be determined during design.

5 PRELIMINARY ARMOR LAYER MODELING

An armor (erosion protection) layer is required to prevent erosion of the cap material when exposed to high shear stresses, such as those caused by high river flows, propeller wash, or other environmental forces such as wind or ice scour. A conceptual-level design of the armor layer is presented below.

5.1 DESIGN BASIS

Cap armor layers are typically designed primarily to resist damage to the cap under flows associated with 100-year return period flood events, with other shear-inducing events (such as propeller- and wind-induced forces, and ice floes) evaluated where necessary. Use of the 100-year return period flood for the design is consistent with recommendations in USEPA (2005) guidance and other cap designs (e.g., Onondaga Lake, Hudson River); however, the cap is expected to remain generally intact even if the 100-year return period flow is exceeded.

The analysis to determine the design flow event employed a standard statistical analysis of peak annual flow records spanning from 1896 to 2012 at the United States Geological Survey (USGS) Little Falls gauge station to estimate flow return periods. A Fisher-Tippett Type II probability distribution was found to best describe these data. The highest flow event observed within the record was a 35,800 cubic feet per second (cfs) event in 1903; however, as this was the consequence of a dam failure as reported by the USGS, this event was not included in the LPR Cooperating Parties Group's (CPG) extreme value analysis. The highest flow observed within the flow record and included in the analysis was associated with Hurricane Irene (20,800 cfs at Little Falls), which corresponds to approximately an 80-year return period event. The predicted flow rates for 100-, 200-, and 500-year events based on the flow record are roughly 22,000 cfs, 25,000 cfs, and 29,000 cfs at Little Falls, respectively. Although the Hurricane Irene flow event does not exceed the predicted 100-year flow, the difference is nominal (less than six percent). Further, water velocities across the entire spatial extent of the river are available from the CPG's hydraulic model for the Hurricane Irene event (Moffatt & Nichol, 2014). For these reasons, the Hurricane Irene flow event was selected for use in this conceptual-level design of the cap armor layer.

Vessel traffic in the study area consists largely of recreational boating, with commercial vessel traffic primarily limited to the lower two miles. Consistent with assumptions made in USEPA's 2014 Focused FS (The Louis Berger Group, 2014), the effects of propeller wash are not expected to control design of the armor layer, and breaking waves along the shoreline due to boat wakes will be negligible compared to erosive forces during flood flows. These potential effects will be assessed during remedial design.

Icing events (such as ice jams, ice floes and shoreline icing) can also cause scour or destabilization of cap materials. The Focused FS (The Louis Berger Group, 2014) discusses ice scour as follows:

> *In colder regions, there is the potential for erosion of a cap due to ice jam formations. The presence of ice reduces the cross-sectional area of the river, thereby increasing water velocities and causing bottom scour. Submerged ice blocks can physically damage the cap as they move downstream, and wind-driven ice scour can occur as ice blocks contact the cap when traveling through shallow areas. In addition, ice blocks that have adhered (frozen) to the surface of the cap can lift off potentially large portions of the cap if the ice blocks become mobile. According to the Cold Regions Research and Engineering Laboratory Ice Jam Database, there have been three ice jam events recorded in the freshwater portions of the Passaic River in Chatham, New Jersey. Although ice forms in the Lower Passaic River, no records of ice jams were found for the FFS Study Area (USACE, 2007a). Therefore, cap erosion due to ice jams are not considered a major concern in the FFS Study Area but should be evaluated more thoroughly during the remedial design. Although ice scour could occur at the shoreline, it could be mitigated via bio-stabilization or installation of armoring materials.*

Although the Area of Focus considered in the Focused FS did not extend upriver beyond RM 8, the reported ice jam events at Chatham are nevertheless still farther upstream than the area considered in this FS. Therefore, it is assumed for FS design purposes that scour due to ice floes or jams does not present a significant design consideration. Ice scour at the shoreline remains a possibility; mitigation measures to reduce the impact of shoreline icing would be considered during remedial design.

5.2 PRELIMINARY ARMOR LAYER SIZING

Preliminary armor sizing was performed using methods presented in Palermo et al. (1998b) based on water velocities and depths determined through hydraulic modeling of the design storm event, and using the following equation to calculate the armor stone size:

$$D_{50} = S_f C_s C_v C_T d \left[\left(\frac{\gamma_w}{\gamma_s - \gamma_w} \right)^{1/2} \frac{V}{\sqrt{g K_1 d}} \right]^{2.5}$$

where:

D_{50} - characteristic stone size of which 50 percent is finer by weight
S_f - safety factor, minimum = 1.1
C_s - stability coefficient for incipient failure (0.30 for angular rock, 0.375 for rounded rock)

C_v - vertical velocity distribution coefficient (1.0 for straight channels and inside of bends; 1.283-0.2log(R/W) for outside of bends)
C_T - thickness coefficient = 1.0 if thickness = D_{100}(max) or 1.5D_{50}(max), whichever is greater
C_G - gradation coefficient = $(D_{85}/D_{15})^{1/3}$
D_{85}/D_{15} - gradation uniformity coefficient (typical range = 1.8 to 3.5)
d - local water depth
$\tilde{a}_w$ - unit weight of water (assumed 62.4 lb/ft^3)[1]
$\tilde{a}_s$ - unit weight of stone (assumed 165 lb/ft^3)
V - local depth averaged velocity
K_1 - side slope correction factor
G - gravitational constant (32.2 ft/sec^2)

The minimum thickness of the armor layer is directly related to the D_{50}, and is typically selected to be 1.5 times the D_{50}. When placing the armor material underwater, the thickness of the armor should be further increased by 50 percent due to a reduced ability to ensure even placement of stone. For purposes of this conceptual design, the minimum thickness of the armor layer is therefore assumed to be 2.25 times the D_{50} (Maynord, 1998).

Results from the hydraulic modeling (Moffatt & Nichol, 2014) and bathymetry were used to determine depth-averaged velocities, local water depths, and bottom slope angle over the area of the site for the design flow. Armor size was calculated for combinations of water depth and velocity for each model cell within the footprint of the LPR study area.

It was assumed that the armor layer consists of angular rock (C_s = 0.3) with a gradation such that D_{85}/D_{15} = 3.5. Rounded rock and a more well-graded layer would result in greater stone size requirements and therefore, depending on the source of stone used, recalculation of rock size may be necessary. The vertical velocity coefficient, C_v, was assumed to be 1.0[2], and the thickness coefficient (C_T) was set to 1.0.

The side slope correction factor, K_1, can be calculated as:

$$K_1 = \sqrt{1 - \frac{\sin^2 \theta}{\sin^2 \phi}}$$

where:

[1] Fresh water is expected to dominate river flow during a flood event, so the unit weight of fresh water (62.43 lb/ft^3) is used. In the event of a tidal surge causing similar water velocities of sea water with a maximum unit weight of 64.1 lb/ft^3, the error associated with the use of the fresh water density is 2.1%, decreasing proportionally with salinity.

[2] The coefficient C_v is applied when using a single characteristic water velocity for large river sections in curved segments. Because critical design sections (as defined by water velocity) were identified primarily in straight, width-constricted river sections, the straight-river C_v value of 1.0 was used globally; the need for cell-specific C_v values will be evaluated during design.

K_1 - side slope correction factor
□ - bottom slope angle
□ - angle of repose (assumed 40 degrees)

As shown in Figure 5-1, depth-averaged velocities within the study area during this conceptual design event ranged from 0.3 to 9.3 ft/sec, with an average of 4.9 ft/sec and median value of 5.2 ft/sec. The computed D_{50} of the armor material ranged from 0.002 to 6.5 inches, with an average size of 1.41 inches and a median size of 1.45 inches. As a practical matter, it would not be efficient to attempt to place armor materials specifically sized to each grid cell within the hydraulic model; rather, this conceptual design identifies six different types of armor material that could be used across nearly the entire river.

The smallest of the armoring materials is coarse sand (D_{50} of 0.1875 inches); the remaining materials are all classified as gravel or larger materials, and include D_{50} values of 0.85, 1.35, 1.82, 2.5, and 5.35 inches. A limited number of grid cells representing an aggregate area of 0.24 percent of the modeled area would require armor materials with a D_{50} of greater than 5.35 inches; due to the unique conditions at these locations, a typical armor material size has not been assigned to these areas. The armor material sizes for all other areas were selected such that they are approximately evenly distributed across the study area, as shown in Figure 5-2.

The minimum armor layer thicknesses corresponding to the design D_{50}s are 0.4, 1.9, 3.0, 4.1, 5.6 and 12.0 inches. From a constructability standpoint, however, placement of armor materials in these dimensions would be impractical. Further, scour due to river flow is not the only design consideration. During remedial design, it will also be necessary to assess the impacts of secondary and tertiary design considerations (such as icing, tidal storm surge events, prop wash and wind) on overall cap design. Therefore, for the purposes of this FS, it is assumed that the armor layers would be 12 inches in thickness except for mudflat areas, where an armor layer of 6 inches is assumed. The limited areas where the design D_{50} is greater than 5.35 inches (which would ordinarily require an armor layer of greater than 12 inches in thickness) will be evaluated during detailed design if these areas coincide with final capped areas; alternative armoring techniques or materials may be considered for these areas.

6 ADDITIONAL TECHNOLOGIES

6.1 IN SITU AMENDMENTS

The use of amendments has been developed and implemented to reduce required cap thickness and to improve their resistance to erosional events and advective transport of COCs by ebullition, non-aqueous phase liquids (NAPL), or groundwater flow and to improve risk reduction and cost-effectiveness of remedies at sediment sites (USEPA, 2013b). Amendments can be applied in bulk onto the sediment surface, mixed in the sediment, added as part of a sand cap, or as a layer within a sand cap, or contained in a reactive core geotextile mat. Information on sites where amendments have been utilized during full-scale or pilot-scale remediation can be found in USEPA's In Situ Remediation Guidance at Sediment Sites (USEPA, 2013b).

Although traditional sand caps are generally effective in containing underlying contamination and preventing exposure of the benthic communities, their effectiveness may be limited under certain site conditions and nature of contamination without significantly increasing its thickness and thereby significantly increasing the dredge depth or reducing the hydraulic capacity, flood storage, and depth of the water body. As noted above in Section 4.4, in situ amendments have been retained in this FS for areas where a 1 foot sand isolation layer may not achieve cap performance objectives as well as in areas where dredging and placement of an engineered cap may not be feasible.

An amended or reactive cap refers to the inclusion of reactive amendments in the granular cap material or in manufactured mats. The additives are selected based on their ability to adsorb or react with contaminants migrating through the cap strata. Activated carbon, bentonite, apatite, AquaBlok®, and coke are examples of reactive amendment materials that have been investigated at the demonstration level or in full-scale applications. Activated carbon and other carbonaceous amendments are effective amendments because of their strong sorbent properties. Dioxins/furans and PCBs are strongly adsorbed by activated carbon (often in a granular form), making them less bioavailable (USEPA, 2013b). Other types of amendments such as Organoclays™ have been effective at sites impacted by NAPLs; however, NAPLs are not believed to be a concern in the LPR study area.

In situ amendments including reactive core mats as well as marine mattresses and other armoring techniques would be evaluated in the design phase to potentially reduce the depth of dredging if it can be shown that these measures would be effective and not result in adverse impacts on flooding and waterway use. The extent and types of in situ amendments, if any, will be determined during design and supported by modeling and/or bench testing.

6.2 ENHANCED NATURAL RECOVERY

Enhanced natural recovery (ENR), sometimes referred to as thin-layer placement, is the addition of a thin layer of clean material over areas where natural recovery processes are already occurring, but the rate of sedimentation or other natural processes is insufficient to reduce risk within an acceptable time frame. The thickness of the material used in thin-layer placement is much less than the thickness of traditional isolation caps and could be as little as a few inches. Thin-layer placement is not designed to provide long-term isolation of contaminants from benthic organisms, therefore long-term monitoring is frequently required in conjunction with ENR.

ENR will be considered during the remedial design and adaptive management phases of the project in areas where dredging and placement of an engineered cap may not be feasible and in areas where conditions are suitable for this technology.

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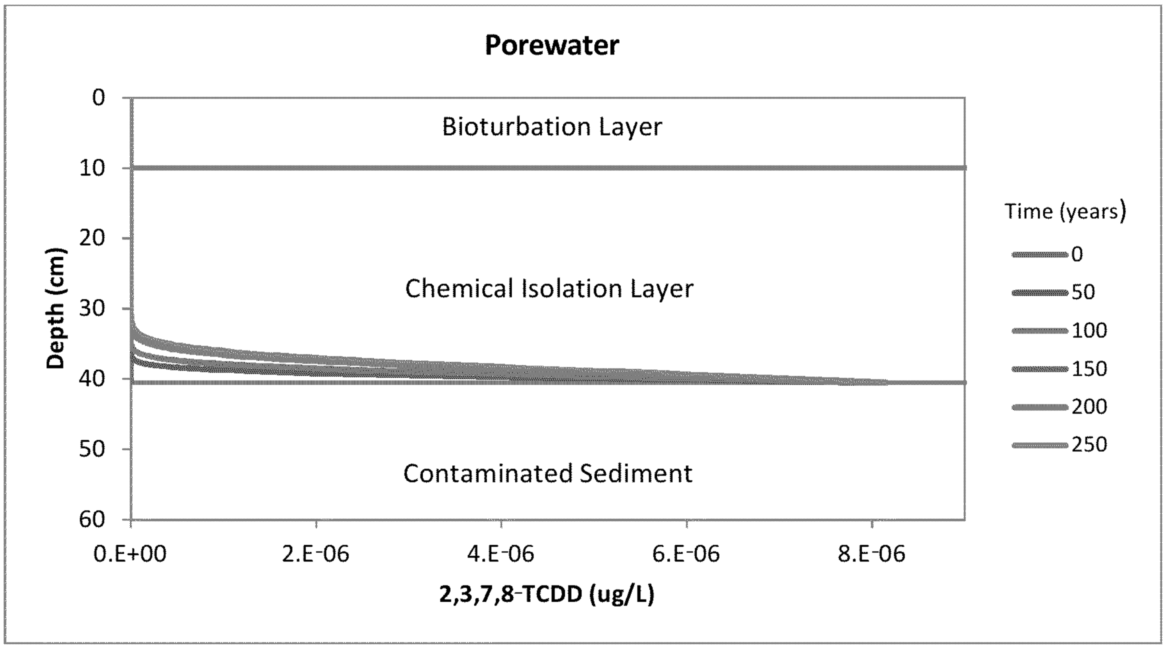
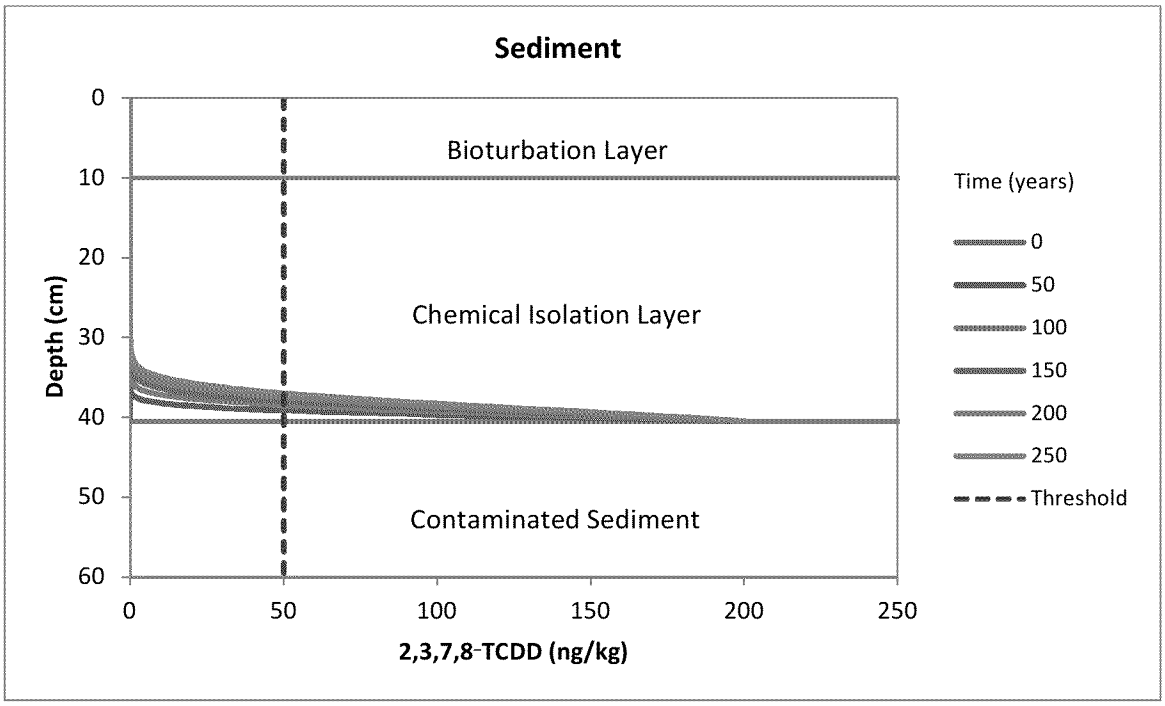
FIGURES

Figure 4-1. Predicted 2,3,7,8-TCDD Concentration Profiles, High Upwelling

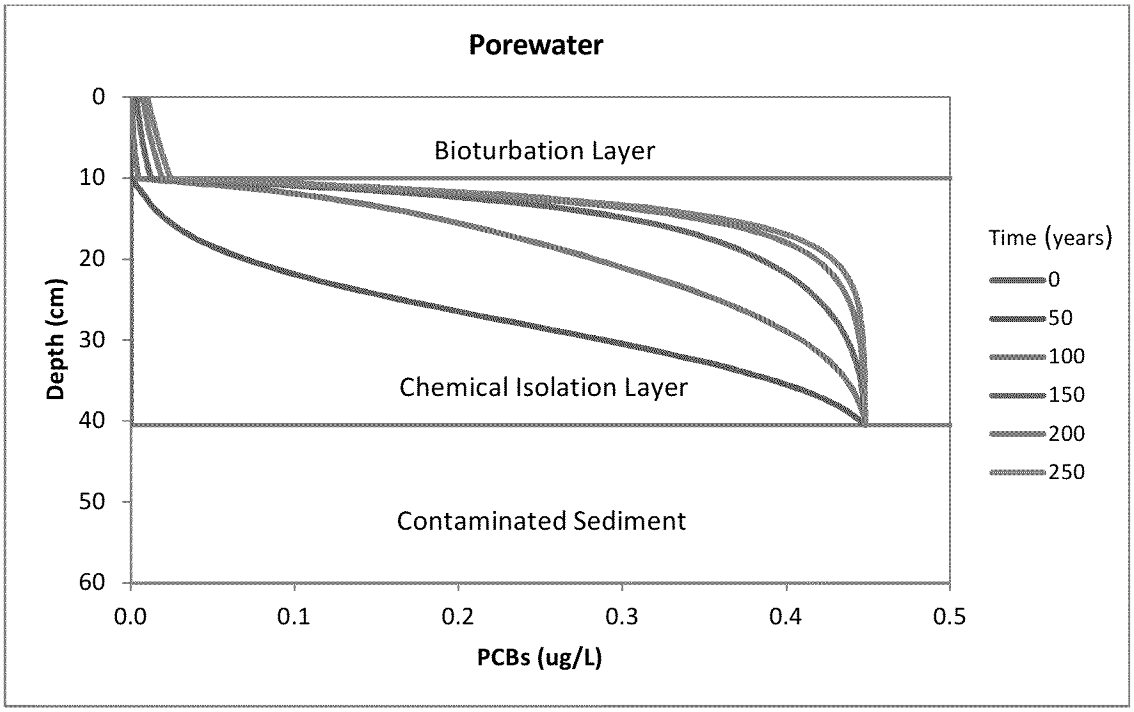


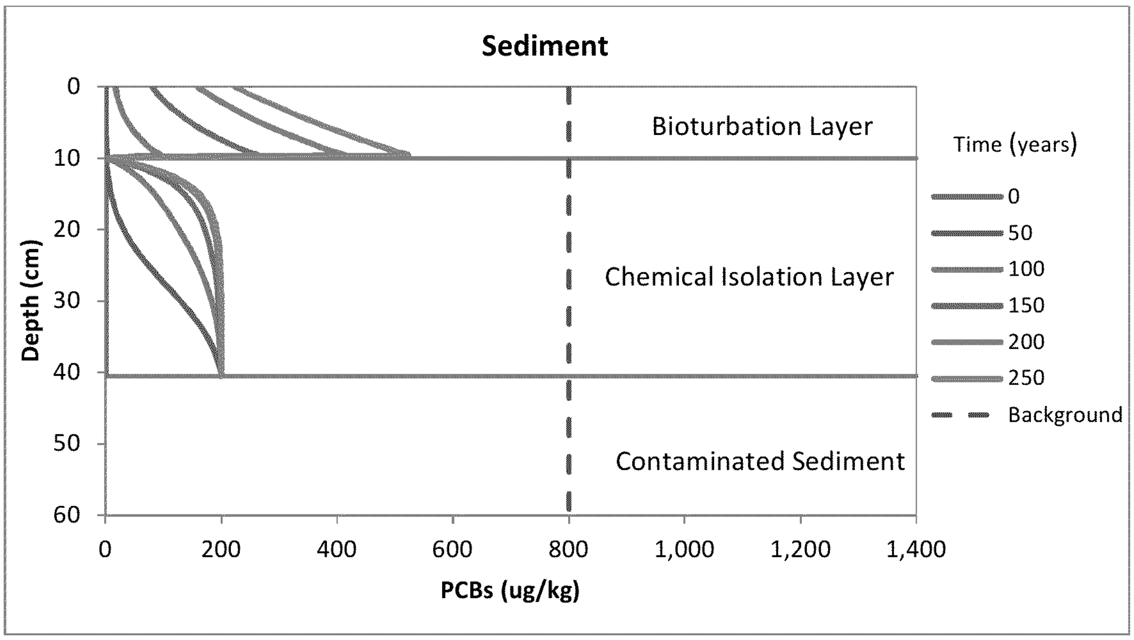


Notes:
Predicted concentrations from CapSim model based on underlying sediment concentration of 10,000 ng/kg, assumed upwelling velocity of 250 cm/yr, and fraction organic carbon (foc) of 5% in bioturbation layer.

Sediment concentrations at bottom of isolation layer are less than underlying sediment concentration due to change in foc in isolation layer.

Figure 4-2. Predicted PCBs Concentration Profiles, High Upwelling





Notes:
Predicted concentrations from CapSim model based on underlying sediment concentration of 10,000 ug/kg, assumed upwelling velocity of 250 cm/yr, and fraction organic carbon (foc) of 5% in bioturbation layer.
Sediment concentrations at bottom of isolation layer and bottom of bioturbation layer vary from the layer below due to changes in foc in those layers.

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Maximum Depth-averaged Velocity (ft/s)

- < 1.00
- 1.01 - 2.00
- 2.01 - 3.00
- 3.01 - 4.00
- 4.01 - 5.00
- 5.01 - 6.00
- 6.01 - 7.00
- 7.01 - 8.00
- 8.01 - 9.00
- > 9.00

0 500 1,000 2,000 3,000
Feet

NOTES:
Predictions from LPR/Newark Bay hydrodynamic model, Moffat & Nichol, September 2014

Figure 5-1
Maximum Predicted Depth-Averaged Velocities for 100-Year Event (Hurricane Irene)

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AECOM
April, 2015

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Characteristic (D_{50}) Armor Material Size (in)

- 0.1875
- 0.85
- 1.35
- 1.82
- 2.5
- 5.35
- >5.35

NOTES:
Predictions from LPR/Newark Bay hydrodynamic model, Moffat & Nichol, September 2014

Figure 5-2
Preliminary Characteristic (D_{50}) Sizing of Armor Material

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TABLES

Table 4-1. Cap Model Parameters Input Table

Parameter		Units	Value	Basis
Contaminant Porewater Concentration	C_0	ug/L	Contaminant Specific	Based on a range of underlying sediment concentrations from site data, an average foc of 5%, and literature partition coefficients
Organic Carbon Partition Coefficient	log K_{oc}	log L/kg	Contaminant Specific	Log Koc for 2,3,7,8-TCDD = 7.39 (from CH2MHill's RM10.9 Final Design, 2013); log Koc for PCBs = 5.65 (NYSDEC Screening Guidance 1999).
Water Diffusivity	D_w	cm^2/s	Contaminant Specific	Values from CH2MHill's RM10.9 Final Design (2013).
Cap Decay Rate	[illegible]	yr^{-1}	0	No decay assumed
Bioturbation Layer Decay Rate	[illegible]	yr^{-1}	0	No decay assumed
Biological Active Zone Fraction Organic Carbon	$(f_{oc})_{bio}$	%	2%,5%	Assumed value for future condition within upper portion of cap (bioactive zone)
Colloidal Organic Carbon Concentration	[illegible]	mg/L	0	Steady-state model not sensitive to this parameter
Darcy Velocity (positive is upwelling)	V	cm/yr	1,10,100,250	Range of potential upwelling velocities
Depositional Velocity	V_{dep}	cm/yr	0	Conservative assumption of no deposition
Bioturbation Layer Thickness	h_{bio}	cm	10	Conservative depth for estuarine conditions
Porewater Bio-diffusion Coefficient	D_{bio}^{pw}	cm^2/yr	100	Lampert,D.J. and Reible, D. (2009b) based on Thoms,S.R.,Matisoff,G.,McCall,P.L., and Wang,X. (1995)
Particle Bio-diffusion Coefficient	D_{bio}^{p}	cm^2/yr	1	Lampert,D.J. and Reible, D. (2009b) based on Thoms,S.R.,Matisoff,G.,McCall,P.L., and Wang,X. (1995)
Depth of Interest	z	cm	Up to 10	Average sediment concentration in bioturbation layer (bioactive zone)
Fraction Organic Carbon at Depth of Interest	$f_{oc}(z)$		2%,5%	Assumed value for future condition within upper portion of cap (bioactive zone)
Cap Materials - Granular(G) or Consolidated Silty/Clay (C)			G	Granular material assumed
Cap Consolidation Depth	$z_{cap\ cons}$	cm	0	Consolidation not modeled for steady-state model, not sensitive
Underlying Sediment Consolidation Due to Cap Placement	$z_{sed\ cons}$	cm	0	Consolidation not modeled for steady-state model, not sensitive
Porosity	[illegible]		0.4	Typical value for loosely packed, medium-grained sand
Particle Density	ρ_P	g/cm^3	2.6	Typical value for sand cap
Chemical Isolation Layer Fraction Organic Carbon	$(f_{oc})_{eff}$		0.10%	Conservative value based on assumption of a typical sand cap
Boundary Layer Mass Transfer Coefficient	k_{bl}	cm/hr	0.75	Lampert,D.J. and Reible, D. (2009b) based on Thibodeaux, L.J. (1996)
Chemical Isolation Layer Thickness	h_{ch}	cm	30.48	Assumed thickness for FS
Cap Thickness	h_{cap}	cm	40.48	The thickness of chemical isolation layer and bioturbation layer
Effective Dispersivity	α	cm	2.8	Based on CH2MHill estimate of effective tidal dispersivity as per RM10.9 Design (2013). Note Reible model dispersivity for non tidal conditions is estimated as 0.05*cap thickness (0.05*40cm=2cm).

Table 4-2. Predicted Steady-State 2,3,7,8-TCDD Sediment Concentrations in Bioactive Zone

Upwelling Velocity (cm/yr)	Concentration in Underlying Sediment (ng/kg)									
	10,000		1,000		500		250		100	
	foc bio		foc bio		foc bio		foc bio		foc bio	
	2.0%	5.0%	2.0%	5.0%	2.0%	5.0%	2.0%	5.0%	2.0%	5.0%
1	1.3	3.2	0.1	0.3	0.1	0.2	0.0	0.1	0.01	0.03
10	6.5	15.7	0.6	1.6	0.3	0.8	0.2	0.4	0.1	0.2
100	**62.8**	**153**	6.3	15.3	3.1	7.7	1.6	3.8	0.6	1.5
250	**153**	**374**	15.3	37.4	7.7	18.7	3.8	9.4	1.5	3.7
Proposed Cap Threshold	50	ng/kg								

Notes:
1. Bold values indicate predicted concentrations exceed proposed cap threshold.
2. foc bio is an assumed foc of the bioactive layer under future conditions.

Table 4-3. Predicted Steady-State PCBs Sediment Concentrations in Bioactive Zone

Upwelling Velocity (cm/yr)	Concentration in Underlying Sediment (ug/kg)							
	10,000		5,000		2,500		1,000	
	foc bio		foc bio		foc bio		foc bio	
	2.0%	5.0%	2.0%	5.0%	2.0%	5.0%	2.0%	5.0%
1	4.4	6.4	2.2	3.2	1.1	1.6	0.4	0.6
10	20.6	30.0	10.3	15.0	5.1	7.5	2.1	3.0
100	194	289	97.1	144	48.6	72.2	19.4	28.9
250	455	698	228	349	114	174	45.5	69.8
Background Value	800	ug/kg						

Note:
1. foc bio is an assumed foc of the bioactive layer under future conditions.